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IV. FERMILAB DOUBLER MAGNET DESIGN AND FABRICATION TECHNIQUES

K. Koepke, G. Kalbfleisch, W. Hanson, A. Tollestrup, J. O'Meara, J. Saarivirta*

ABSTRACT

During the last year, the Fermilab Doubler magnets have benefited from a development effort to upgrade the performance of the superconducting magnets. This paper presents the results of this effort. The design philosophy and the fabrication techniques used on current magnets will be discussed, along with innovative laminated tooling which has been designed to give Fermilab a two dipole a day production capability. Specific topics to be discussed are coil geometry, coil winding techniques, coil clamp collars, buss geometry and insulation, integral quench heaters for quench protection, coil twist, coil helium irrigation and assembly techniques that assure azimuthal preload and accurate coil size.

INTRODUCTION

In order to minimize the construction and operation cost of the Fermilab Energy Doubler project and also due to space limitations in the existing 500 Gev synchrotron tunnel, a relatively simple "warm" iron, cold bore magnet design [1] was adopted. Three distinct modules are separately fabricated and assembled to form a complete magnet: the collared coil, the cryostat and the iron shield yoke.

The coil package for the dipole consists of a two-shell design with the first 10 turns of the inner shell at the ends separated with .100" spacers to reduce the peak field at these locations. By varying the azimuthal coil angles of the inner and outer shell, the two-dimensional field region can be adjusted to cancel the sextapole and decapole terms present in the ends of the magnet.

By virtue of its location between the rigid coil clamp collar and the iron yoke, the cryostat need not be self-supporting and is fabricated out of thin stainless steel sheet metal. Precise alignment of the collared coil assembly relative to the iron yoke is assured by means of rigid G-10 force transfer blocks located periodically within the cryostat. The cryostats come partially assembled from several vendors.

The magnetic shield differs from conventional magnet yokes only in their cross section. They are assembled out of laminations into left and right halves in a stacking fixture and joined around the coil and cryostat assembly to complete the magnet.

Over 100 collared dipole assemblies have been completed. Roughly half of these have been inserted in cryostats with iron shields and are in various stages of installation in the synchrotron tunnel. As problems became evident during their construction and testing, they were corrected or improved. Laminated tooling was designed to improve coil accuracy and production rate. Coil measuring fixtures were constructed to monitor coil sizes. Conductor motions have been reduced with increased preload. A new type 5 coil clamp collar has been adopted which has a higher resistance to fatigue and is torsionally more rigid. Heaters have been installed in the dipole for quench protection and a new buss geometry has been adopted.

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*Fermi National Accelerator Laboratory, P.O. Box 500 Batavia, Illinois 60510, operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.

The prototype Doubler quadrupole magnet was a "warm" iron, cold bore, three-shell design. Seven magnets of this type have been constructed and successfully tested. Recently, a two-shell quadrupole design was adopted to simplify fabrication and allow a higher production rate.

COIL FABRICATION AND MAGNET ASSEMBLY

The sequence of fabricating a collared dipole coil assembly starts with the winding and hot molding of two identical 35 turn inner coils. Our original technique of "saddle" winding these coils was abandoned in favor of our "pancake" technique. This technique consists of winding a flat coil around an articulated key mounted on a .060" steel retainer sheet. After winding, the coil is covered with a second .060" steel retainer and transversely compressed by means of side rails to a dimension approximately equal to the desired outer arc length of the finished coil. The side rails are then fastened to the retainer sheets, resulting in a "pancake sandwich". This is formed around a mandrel using a female mold in a 22' long press and cured, yielding the conventional "saddle" coil configuration. This technique has proved to be fast and accurate.

The outer coils are "saddle" wound using the inner preformed coils as a winding mandrel. This technique has resulted in adequate conductor placement accuracy due to the smaller number of turns (21) in the coil. In order to provide for LHe edge cooling, a layer of .021" thick interrupted G-10 is placed between the inner and outer coils.

The cured two-shelled upper and lower coil halves are placed on the assembly mandrel, covered with .030" thick premolded mylar ground insulation (later to be Kapton) and fitted with 4" long collar sections. The loosely collared coil assembly is placed into a pair of massive channel-shaped fixtures which provide precise vertical and horizontal constraints to the collar as it is sized in a 3200 ton hydraulic press. Finally, the assembly mandrel is removed from the coil by means of a ratched-action hydraulic cylinder and the collar is welded on both sides by automatic welding machines.

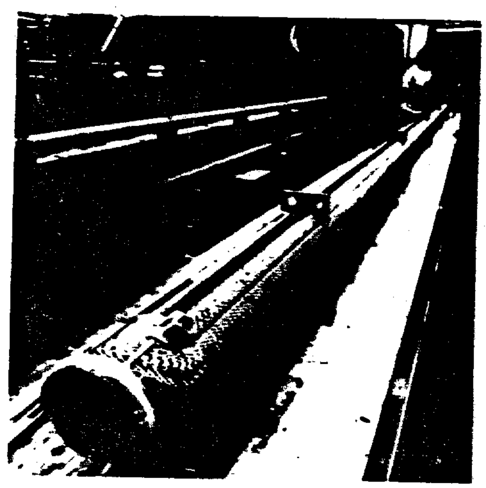

Fig. 1 Dipole lower coil

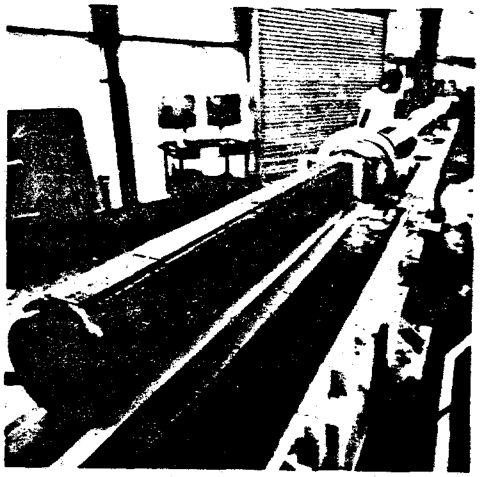

Fig. 2 Collared dipole coil half inserted in cryostat

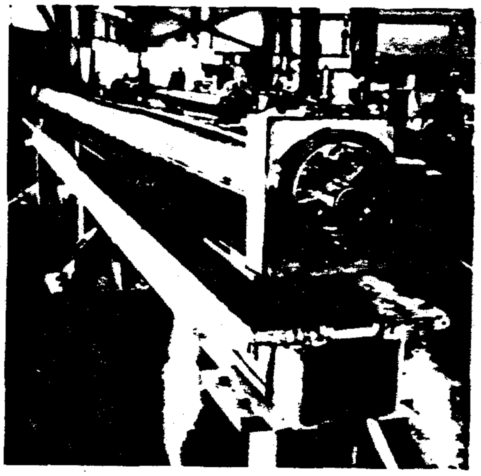

Fig. 3 Half yoked dipole

A magnet is completed by pushing a collared coil into a prefabricated cryostat, welding on the cryostat end closure pieces and finally fitting the two halves of the prefabricated yoke. Note that this production sequence lends itself to production line techniques. With the present manpower available, a production rate of 5 collared coils per week has been achieved with 250 manhours required per collared coil. The in house manpower per magnet is approximately 400 manhours if we add the cryostat, yoke and inspection steps. It is expected that the production rate can be doubled with the efficient use of available tooling and three fully staffed shifts.

The quadrupole magnet fabrication utilizes the same principles devised in the dipole development program except that the coils are all saddle wound. The four sets of coils are wound as double shells, pressed and cured in the same manner as the dipoles. In order to support the four individual coils, the collars are applied from four sides rather than two, necessitating the application of collars one at a time.

TOOLING

The equipment available to produce collared dipole coil assemblies consists of three 22' long winding machines for producing coils, two 22' long presses with integral molds for forming coils and two 3200 ton presses for sizing and welding collared coils. In addition, there exist several sets of inner and outer winding mandrels, assembly mandrels, and channel tooling used to size the collars.

All molds, winding mandrels and keys presently in use are made of laminations. In our experience, 22' long tools, even in simple shapes, cannot be economically made to a .0005" tolerance. However, relatively inexpensive dies using Elox cutting techniques can produce complex cross sections to .0005" tolerances and a lamination uniformity of .0001" is within the present state of the art. Tools assembled out of stacked laminations are therefore uniform thru-out their length and make replication of tooling very simple.

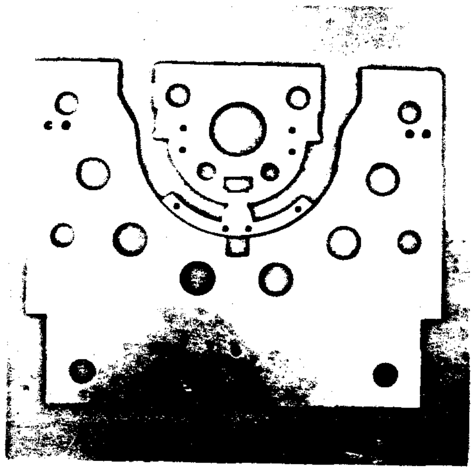

Fig. 4 Outer dipole mold laminations

To achieve these tolerances, the laminations are made out of mild steel. All bearing surfaces of the tooling are therefore fitted with hardened steel inserts of simple rectangular cross section which can be ground to a .0005" tolerance. These inserts also allow us to change the molded azimuthal angles of subsequent coils to compensate for systematic field errors measured in completed magnets.

CONDUCTOR PLACEMENT ACCURACY

In order to reduce the AC loss inherent in ramped magnets, the superconducting cable adopted for the Doubler magnets was a Rutherford type cable made by twisting 23 strands, each of .027" diameter, into a (.044" - .055") x .307" keystoned cross section in a Turkshead die. The keystoned shape allows for proper conductor stacking in the cylindrical coil geometry and is porous to allow for LHe irrigation. The porosity of coils is maintained by the use of a non-adhesive 7/12 lap layer of .001" x .375" Kapton for electrical insulation followed by a .125" gap helical wrap of .007" x .25" B-stage epoxy impregnated glass tape for bonding.

The typical mean azimuthal arc length vs. applied pressure behavior of a dipole inner coil is plotted in Fig. 5. Rigid and accurate conductor placement of these porous coils is obtained by compacting the coils during assembly into a split collar. The collar presents a rigid, precise radial and azimuthal outer boundary to the coils.

To the extent that the coils act like piece

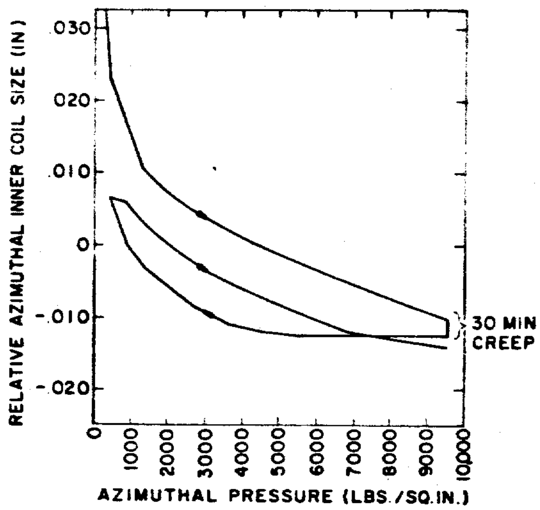

Fig. 5 Inner dipole coil size measured relative to 2.145", the mold dimension.

wise linear springs in the azimuthal direction, the upper to lower coil boundary within the collar at a given azimuthal force is determined by half the difference in azimuthal coil size measured at that force. These coil sizes (Fig. 6) are regularly measured as part of our ongoing quality control program. Although the coil sizes vary within a .020" range, resulting in a variable preload, the coil boundaries for collared coils are on the average within .001" of their calculated position.

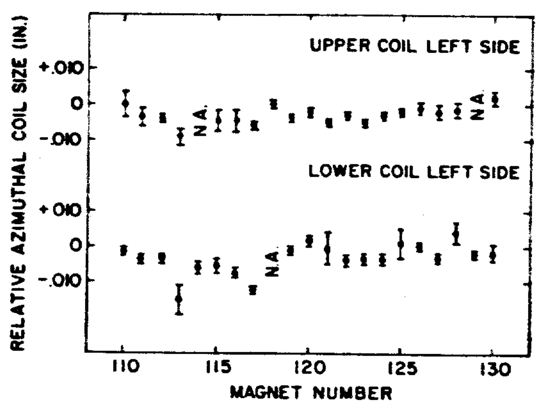

Fig. 6 The inner dipole coils were measured at an azimuthal pressure of 4780 lbs./sq. in. The error bars represent the standard deviation of 11 measurements taken along the length of the coil.

The bore dimension of the magnet is determined by the wall thickness of the coils, which reproduce within .001" due to the small cumulative tolerance in this direction. Strain gauge measurements on the OD of the collar and the ID (bore) of the coils have shown that the radial compression of the coils is less than .001".

The azimuthal conductor placement within individual coils is harder to control. The conductor distribution within the inner dipole layer, the layer whose conductor distribution is most difficult to control, has been optically measured on cross sections of collared dipoles. The measurements indicate that the conductors have a mean position error relative to the correct position of less than .001" with a standard deviation of .003". For the outer dipole coils and the quadrupole coils, this error is expected to be less due to the smaller number of conductors present.

Calculations and measurements indicate that the conductor placement of the magnet ends are an order of magnitude less critical than the two dimensional part of the magnet. In this case, the contour of the ends is assured by molding precision G-10 spacers to the ends during the coil curing stage. These spacers remain with the coil during assembly.

CONDUCTOR MOTION AND PRELOAD

Measurements[2] performed on 1 ft. long prototypes of the Doubler superconducting dipoles indicated that the azimuthal compaction of coils in energized magnets can be limited to a few thousands of an inch with adequate azimuthal preload. Early attempts to size coils such that this preload is trapped in the collar on full sized magnets failed for the following reasons: The coil clamp collar used to be bonded at 200°F with heat cure epoxy. During this process, the trapped coils under the combined effect of heat and pressure collapsed. This effect has been measured to start at 125°F.

The preload that remained was further reduced by the differential coil to collar shrinkage from room to LHe temperature. The difference in azimuthal coil size $\Delta \ell$ (P) measured at room temperature and LN temperature both at azimuthal pressure P has been measured to follow the equation:

$$\frac{\Delta\ell(P)}{\ell}\Bigg|^{300^\circ K}_{78^\circ K} = (3.55 \pm .35) \times 10^{-3} - (2.3 \pm .22) \times 10^{-7}\,(P-P_0) \qquad \text{(Eq. 1)}$$

where P_0 equals the pressure at which the sample is cooled. All pressures are expressed in lbs./sq. in. The $(P-P_0)$ term accounts for the difference in Young's modulus at the two temperatures.

In order to assure adequate preload, the inner and outer coils of the superconducting dipole have to be molded .040" and .005" oversize in the azimuthal direction. The collars are now welded to eliminate temperature induced coil yielding. Upon cool down, at least 4700 lbs./sq. in. of azimuthal preload remains in the inner coil. This has been verified by slitting the collar at the median plane of the dipole and measuring the force required to return the sprung collar back to its nominal dimension at room temperature and LN temperature.

Conductor motion in the superconducting dipoles has been limited to less than .003" in both the azimuthal and radial direction at 45 KG. The axial motion at this field has been measured for E22-43 and equals .050". The motion related field perturbations as a function of current are therefore dominated by the two-dimensional part of the magnet.

COLLARS

Fatigue tests performed on 1" sections of the type 4 collar previously used on the dipoles predicted their failure after 10^6 magnet cycles. Furthermore, the collar was unable to contain the coil preload without excessive deformation and had insufficient resistance to axial torques.

A new "solid" type 5 collar design has been adopted that overcomes these problems. The fatigue point has been raised to 10^7 cycles, an order of magnitude greater than the anticipated life of the accelerator. Any twist present in the collared coil assembly after welding is measured relative to a surface plate and reduced to less than 3 milliradians with a torque fixture. The collar is then surface coated in place with low viscosity room cure epoxy. It penetrates .1" and effectively results in a tube of this wall thickness to counteract any torques present.

COIL FATIGUE

The premature failure of the type 4 collar under repeated small motions prompted a test of the inner dipole coil under similar conditions. The cyclical azimuthal pressure and the resultant conductor motion that the coil experiences during a magnet current cycle was approximated by applying an azimuthal variable pressure at a rate of 2 cycles per second. The test was performed with the sample immersed in LN. A comparison of the azimuthal coil size measured at the start of the test and after the sample experienced 10^6 pressure cycles showed no measurable size reduction or any other visible signs of damage.

BUSS LEAD

Unlike the other conductors in the magnet, the buss electrical insulation has to withstand 3 KV. To obtain the radial clearance in the magnet for the additional insulation, the buss cable was fashioned out of undersized .025" diameter strands to a cross section of (.043" - .049") x .286". This buss is insulated with 4 layers of 7/12 lap .001" x .375" Kapton followed by an armor layer composed of alternating dry and B-stage impregnated .007" x .25" Kevlar tape helically wrapped with a butt lap.

HEATERS

Two heaters, one redundant, have been installed in the dipoles as part of a proposed quench protection circuit for the Doubler. The purpose of the heaters is to initiate a uniform longitudinal quench in the superconducting turn immediately adjacent to the heater. This quench rapidly propogates in the transverse direction from turn to turn, permitting the magnet to absorb its stored energy without damage.

Each heater consists of a .005" x .200" stainless steel strip wound under the glass tape of the complete first turn of an outer coil. It faces away from the coil and is insulated from the turn by a .010" strip of Kapton.

QA QUADRUPOLES

The prototype QA quadrupole was a 3.25" bore, 3-shell design. The tooling for this magnet was designed for accuracy and sufficient preloading capability, both of which were attained.

The first several quads did not attain a preload internally. The loss of preload was traced to the heat cure cycle of bonding the collars. The last two quads were then bonded with room temperature cure epoxy. They did achieve azimuthal preload. The verification of preload was obtained by magnetic field measurements under excitation. The 12-pole component is sensitive to change in the coil size. By calculation, the ratio of the 12-pole to the 4-pole component (i.e. quadrupole) at 1 inch radius changes by 1 part in 10,000 for a 0.001 inch azimuthal squeeze. Adequately preloaded coils will then show a constant 12-pole ratio with varying excitation current; a change will indicate motion. The heat cured collared assemblies show a 12-pole ratio changing with excitation (Fig. 7A). The magnitude of the observed change in this ratio agrees well with independent mechanical measurements of the coil motion under excitation. The room temperature cured collared assemblies (Fig. 7B) show a constant value for this ratio, indicating a motion of less than 0.001".

QB QUADRUPOLE

The production QB quadrupole is a 3.5" bore, two-shell design. Dipole tooling techniques have been incorporated to produce tooling that will allow a high production rate. A spacer has been incorporated in the inner coil which reduces the 20-pole a factor of 5 over the QA design. The first QB magnet tested reached 5400 A (22KG/in.) in three quenches. A preliminary harmonic probe analysis indicates no conductor motion in the coils.

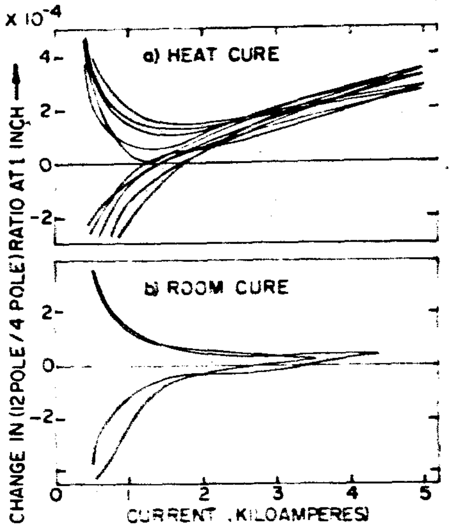

Fig. 7 QBA Magnet 12 Pole to 4 Pole Ratios.

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